Measurements of Top Quark Pair Production Cross Section and Properties at DØ

- Experimental setup
- Top pair production and decay at Tevatron
- Top quark pair cross section
- Top quark branching fractions into b-quarks
- Color-flow structure in top quark pair events

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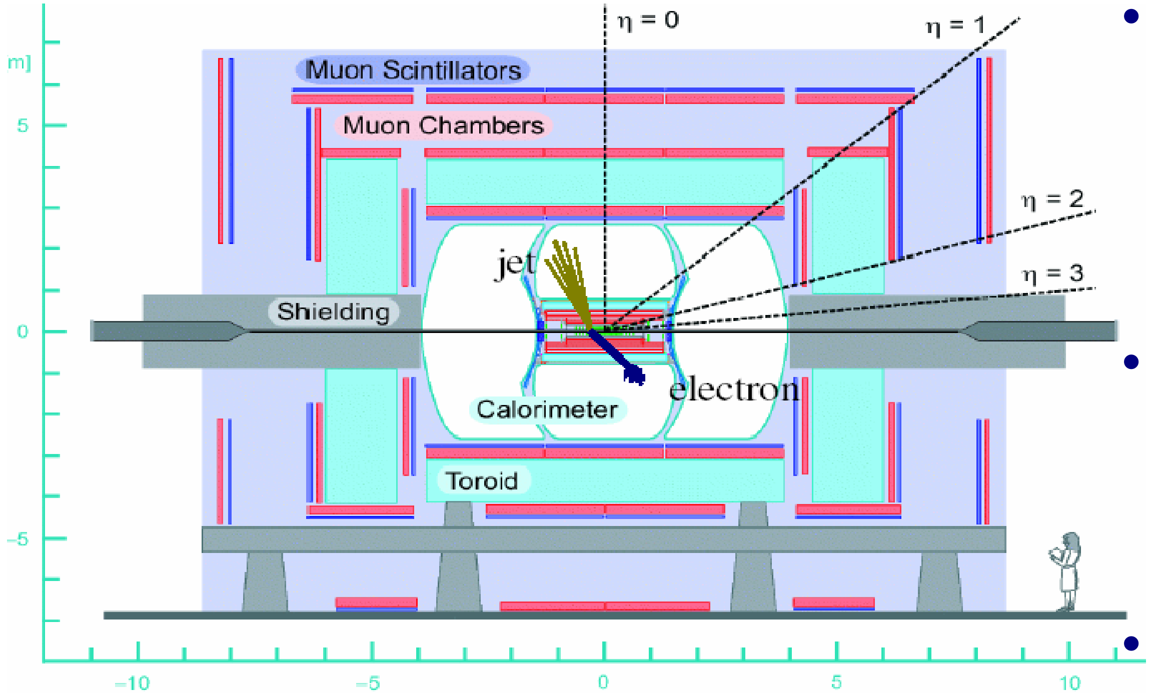
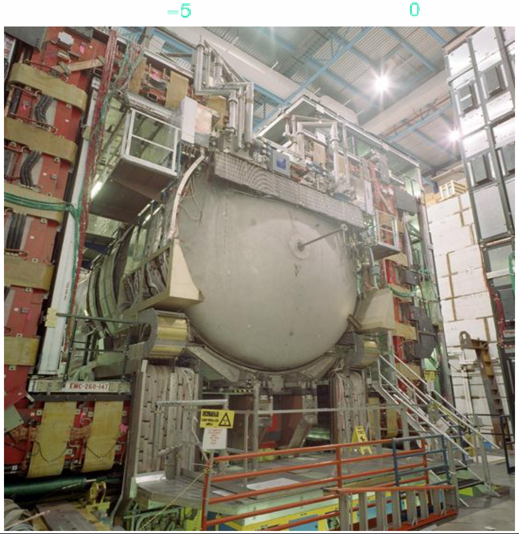
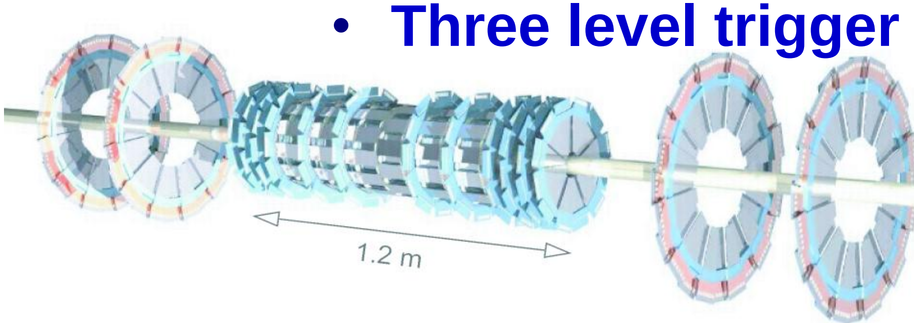
The DØ Detector





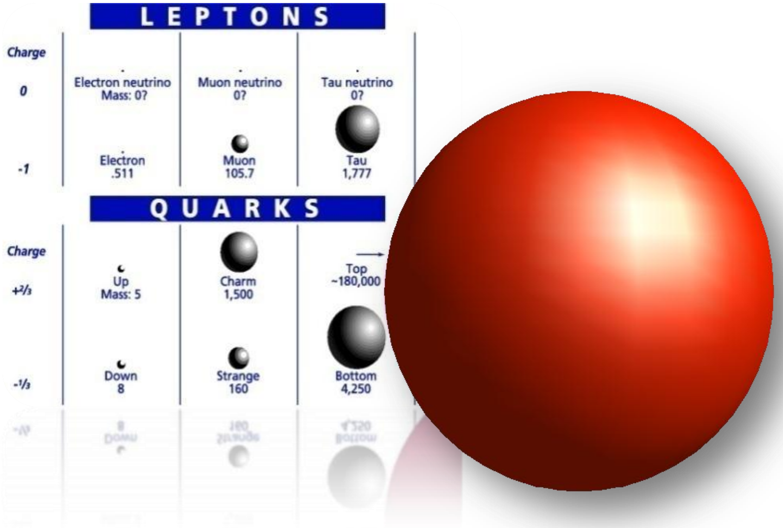
- **Tracking**
  - **Momentum measurement of charged particles**
  - **Vertex and b-jet identification**
- **Calorimeter**
  - **Energy measurement of jets, electrons and neutrinos**
- **Muon system**
  - **Momentum measurement of muons**
- **Three level trigger system**



Top Quark Physics

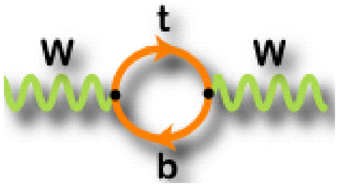
Top Quark is unique

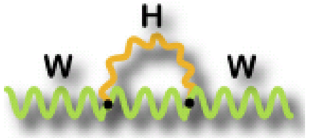
- **Heaviest fundamental particle now**
  - **Mass = 173.3 ± 1.1 GeV**
  - **~40 times heavier than bottom quark**
- **Strong coupling to the Higgs**
  - **Constrains on Higgs mass**
- **Very short lifetime (~ 5×10^{-25} s)**
  - **Decays before hadronization and makes it the only "bare quark"**
  - **Decays almost 100% of the time to *Wb***



Top Quark Physics is a rich field

- **Production rates and properties**
- **Precise test of SM and search for new phenomena**





$\Delta M_W \sim M_{top}^2$ $\Delta M_W \sim \ln M_H$

Top Pair Production and Decay

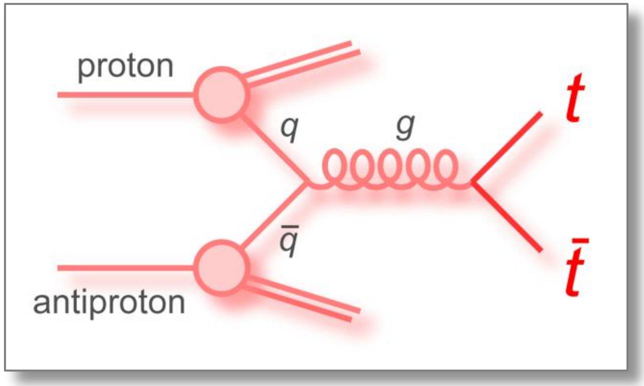
Pair production via strong production

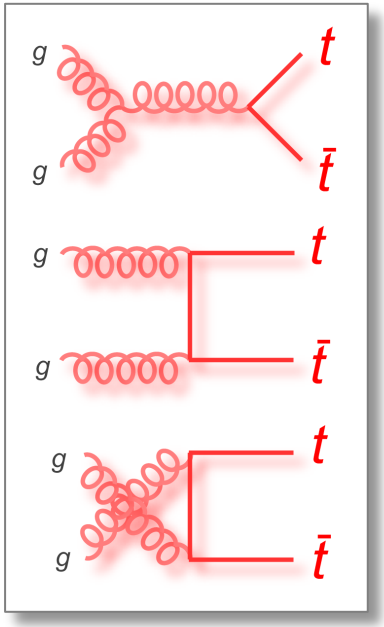
σ_{LHC} ~ 187 pb (7 TeV)

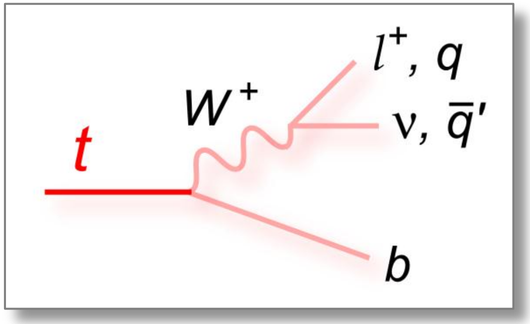
- **Discovery mode (1995)**
- **Main production mode at Tevatron**

$$\sigma_{NNLO} = 7.46 \pm^{0.48}_{0.67}\ pb$$ [PRD 78, 034003 (2008)]

M_t = 172.5 GeV

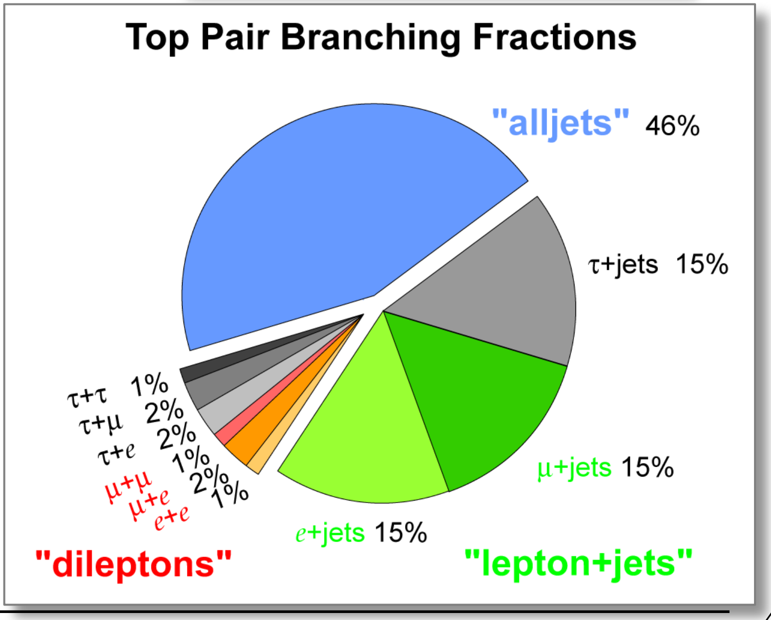




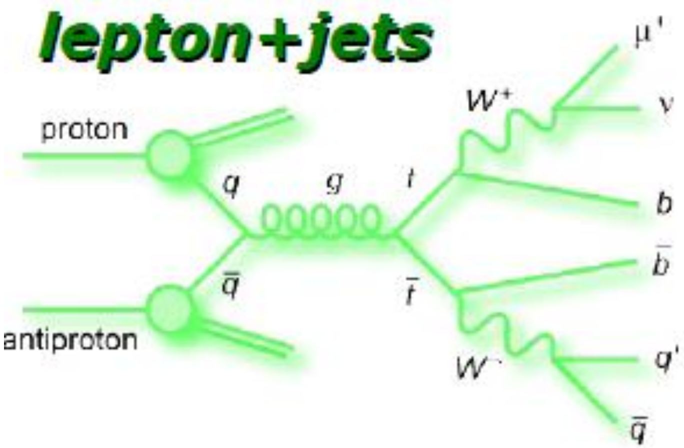


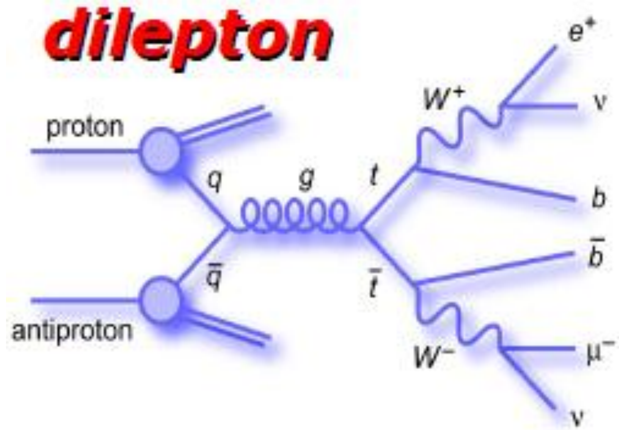
85%

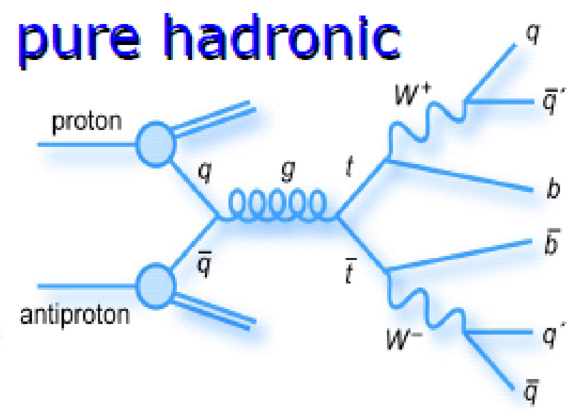
15%



Signal and Background







Isolated, energetic leptons

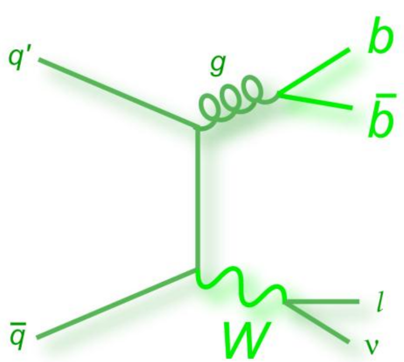
Large missing Energy (neutrino)

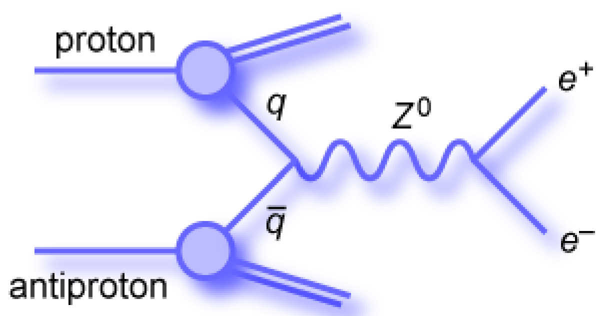
High momentum (b-)jets

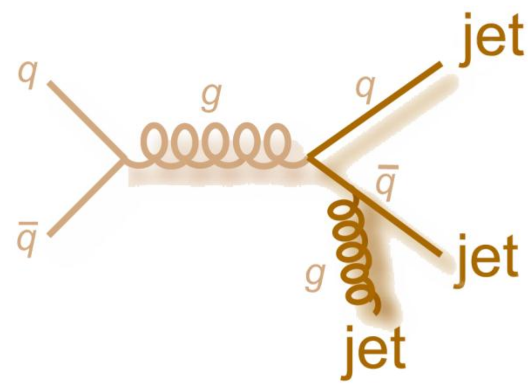
Dominant background: W+jet

Dominant background: Z+jet

Dominant background: Multijet



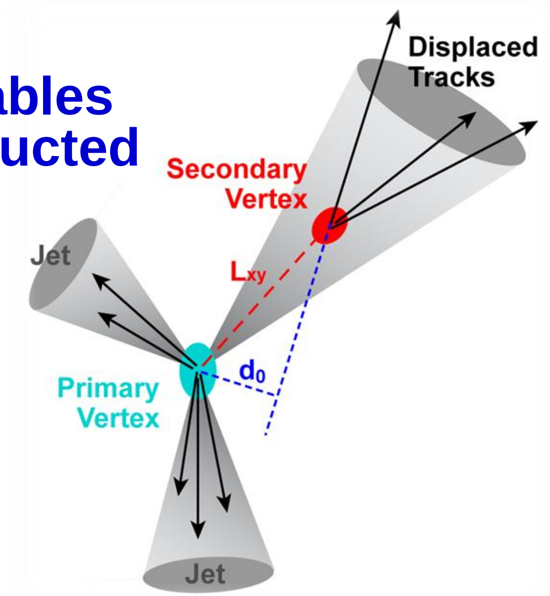


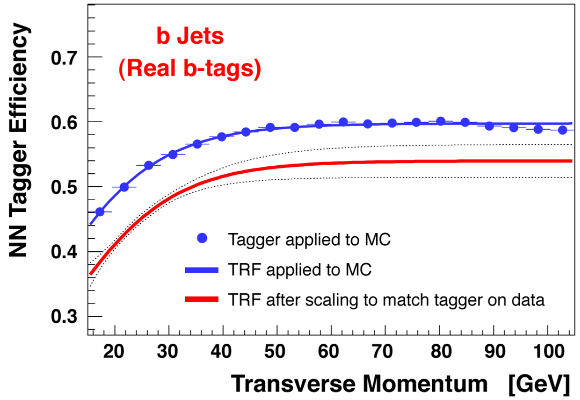


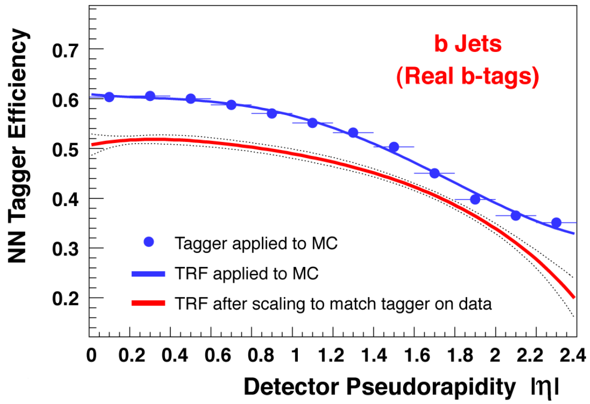
b-jet Identification (b-tagging)

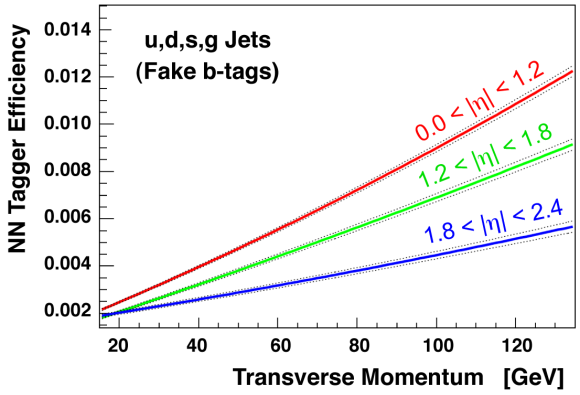
Separate b-jets from light quark and gluon jets

- B-hadron travels some millimeter before decay
- Use a Neural Network algorithm with input variables based on track impact parameters and reconstructed secondary vertex
  - Displaced tracks & vertex
  - NN discriminant output
- Reject most *W/Z*+jets background
- Require single-tag or double-tag

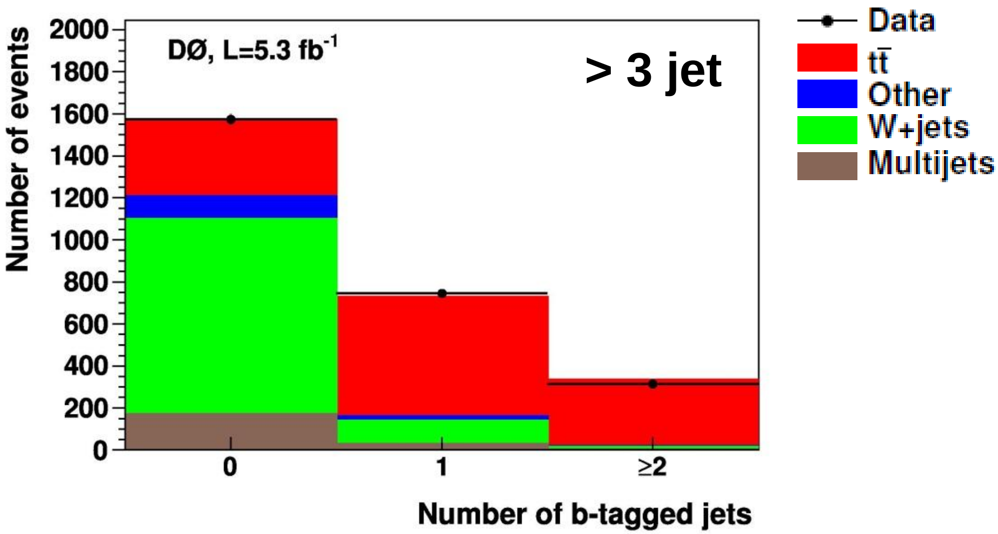


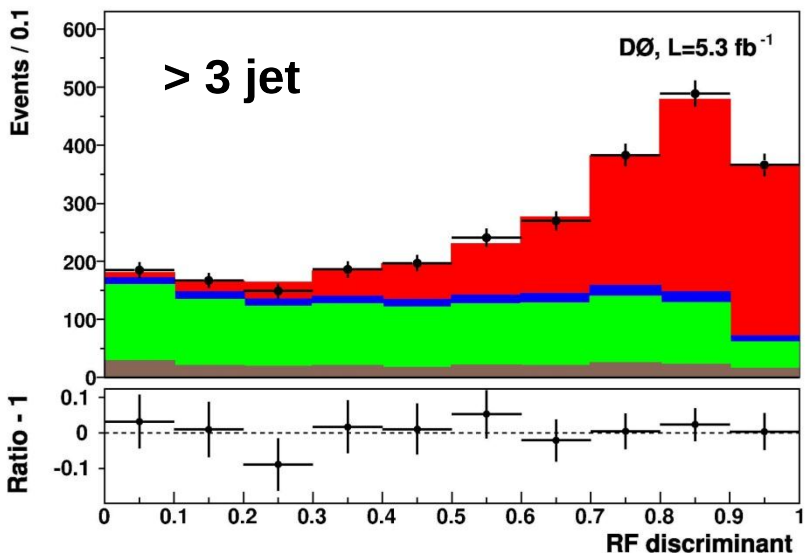






Lepton+jets Channel





Two Analysis Methods

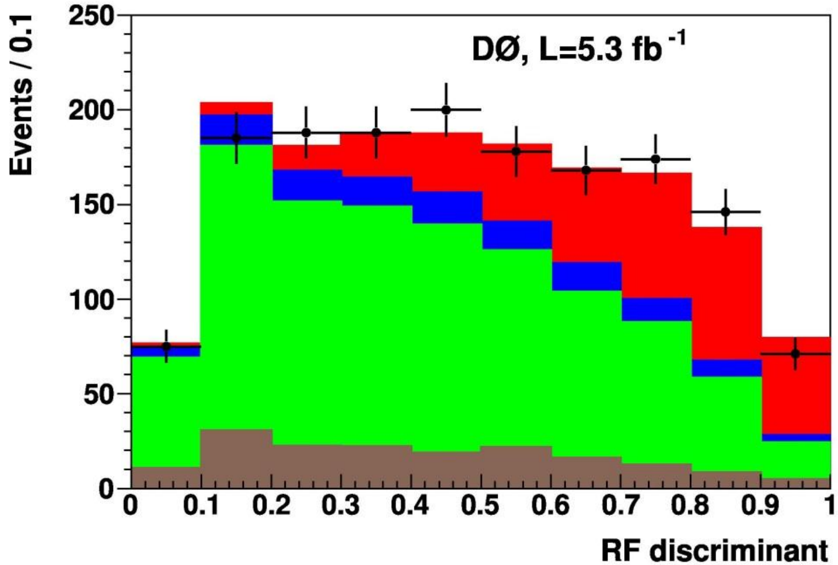
- Use b-tagging to suppress background
  - Form binned likelihood from data, $t\bar{t}$ cross section and predicted background, maximize it as function of $\sigma_{t\bar{t}}$ and nuisance parameters
  - $\sigma_{t\bar{t}} = 8.13 \pm 0.25\ (stat)\ ^{+0.99}_{-0.86}\ (syst)\ pb$
- Use kinematic discriminant to distinguish signal from background
  - Topological method (no b-tagging)
  - Fit discriminant output to data in all channels to extract cross section
  - $\sigma_{t\bar{t}} = 7.68 \pm 0.31\ (stat)\ ^{+0.64}_{-0.56}(syst)\ pb$

Lepton+jets Channel

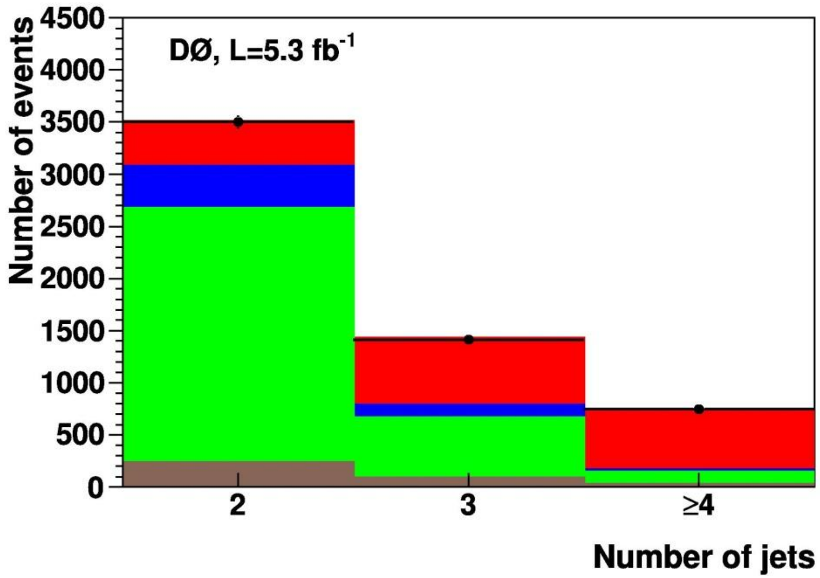
Combination

- **Use both kinematic information and b-tagging information**
- **Construct discriminant for channels dominated by backgrounds, otherwise use b-tagging method; multiply likelihood functions in each channel and fit to data**
- $\sigma_{t\bar{t}} = 7.78\ ^{+0.77}_{-0.64}\ (stat+syst+lumi)\ pb$

>3 jet, 0 b-tag

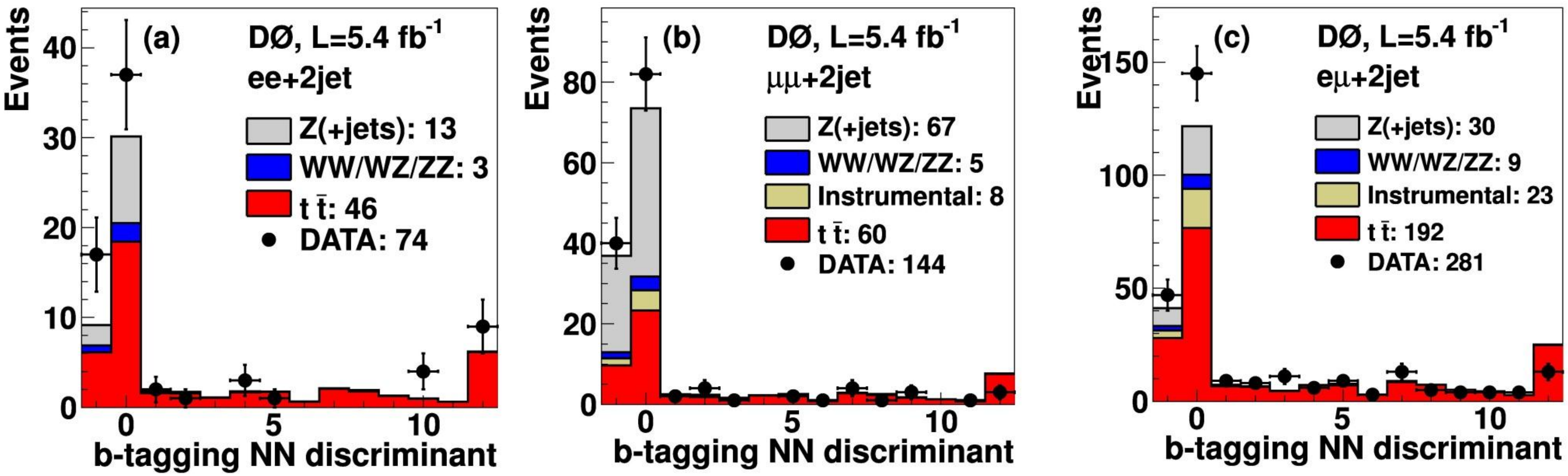


1 b-tag



PRD 84, 012008 (2011)

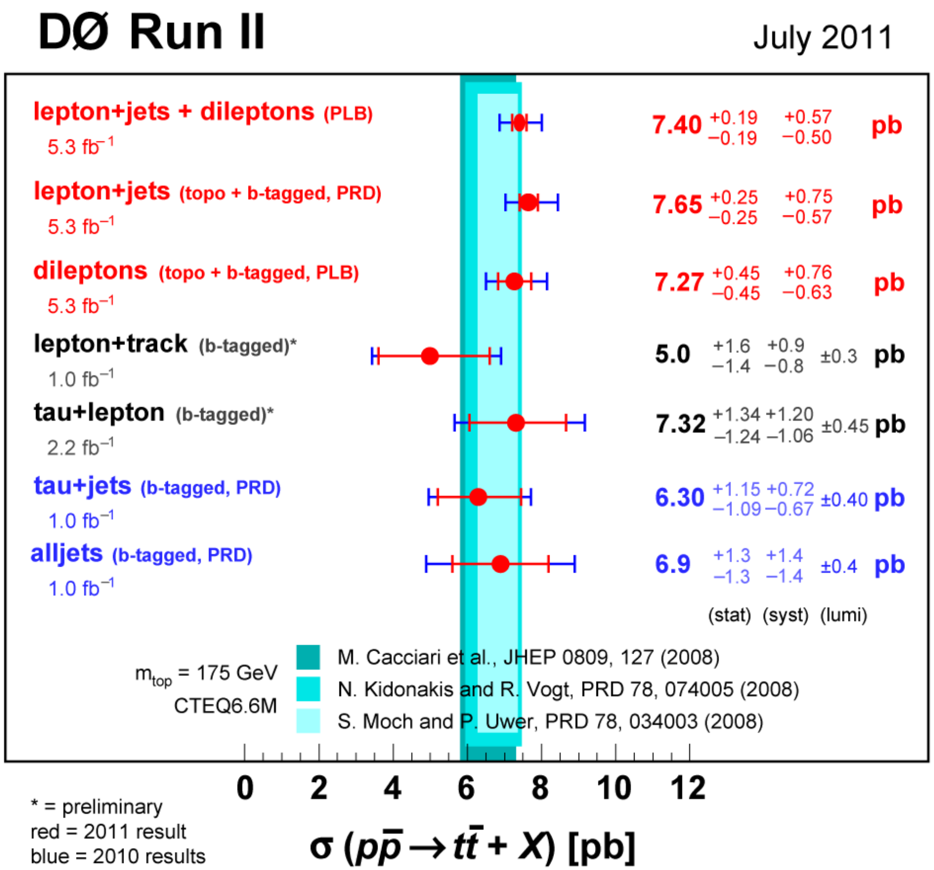
Dilepton Channel



Make full use of B-tagging NN discriminant output information

- **Analysis channels: ee, μμ, eμ, simultaneous fitting on NN output**
  - **High purity of $t\bar{t}$ sample, systematic uncertainty dominate**
  - $\sigma_{t\bar{t}} = 8.05\ ^{+0.50}_{-0.48}\,(stat)\ ^{+1.05}_{-0.97}\,(syst)\ pb$
- **Use nuisance parameters to constrain systematics with data itself**
  - $\sigma_{t\bar{t}} = 7.36\ ^{+0.90}_{-0.79}\,(stat+syst)\ pb$
- **Combine with lepton+jets measurement (complementary)**
  - $\sigma_{t\bar{t}} = 7.56\ ^{+0.63}_{-0.56}\,(stat+syst)\ pb$ **arXiv:1105.5384**

Summary of Top Pair Production Cross Section



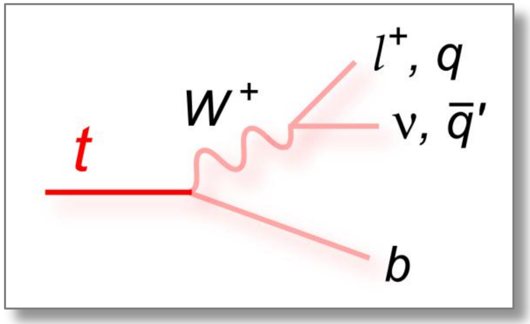
- **All measurements consistent with Standard Model**
  - **Probe new physics**
  - **Best experimental errors comparable to theoretical ones**
- **Important to measure different channels**

Top Quark Decay Branching Ratio

Theory from standard model

$$R = \frac{Br(t \to Wb)}{Br(t \to Wq)} = \frac{|V_{tb}|^2}{|V_{tb}|^2 + |V_{ts}|^2 + |V_{td}|^2} \sim |V_{tb}|^2$$

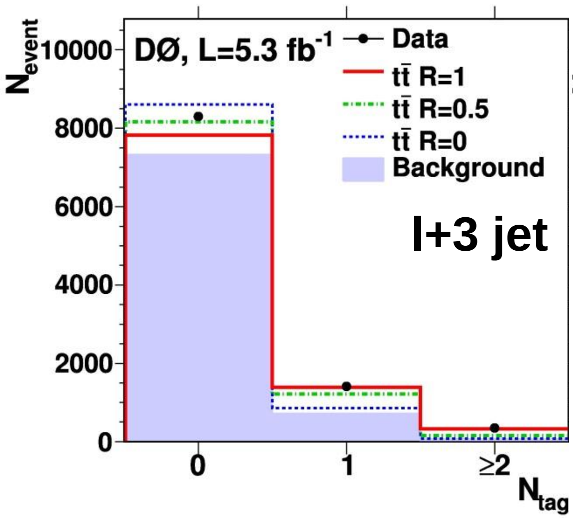
- Unitarity & experimental constraints: $0.99821 < R < 0.99836$
- If significant deviation seen from the SM ratio, search new physics
  - Additional quark families
  - Non-SM production/decay

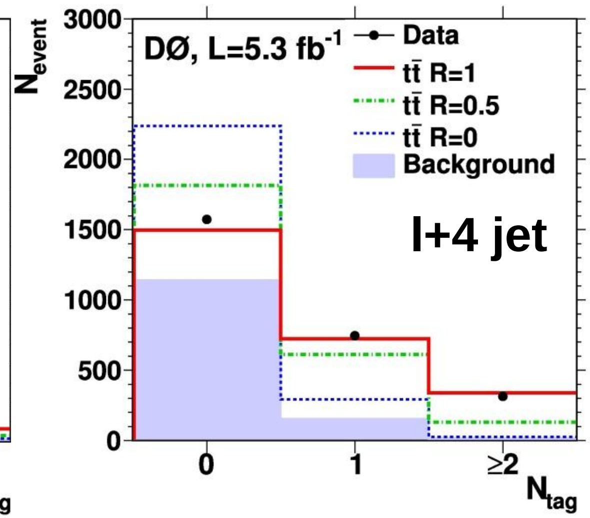


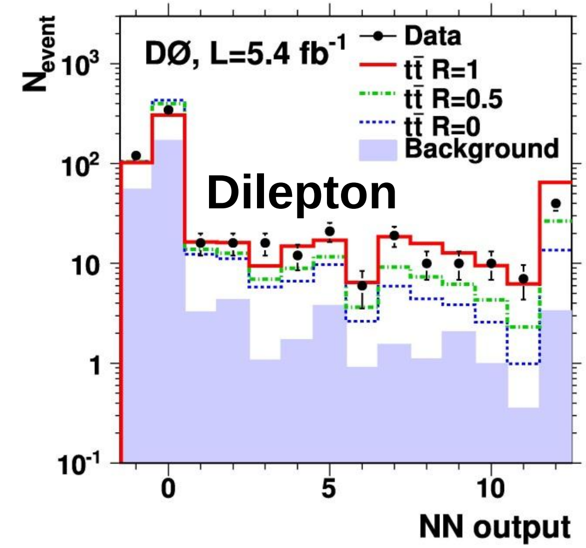
Measurement from experiment

- Remove assumption B($t \to Wb$) = 1 and measure R
- Forming likelihoods and simultaneous fitting of R and $\sigma_{t\bar{t}}$
- b-jet identification important
  - Lepton+jets channel: count number of b-tagged jets
  - Dilepton channel: NN b-tagging discriminant output

Top Quark Decay Branching Ratio







Lepton+jets: R=0.95±0.07 (stat+syst) **Dilepton: R=0.86±0.05 (stat+syst)**

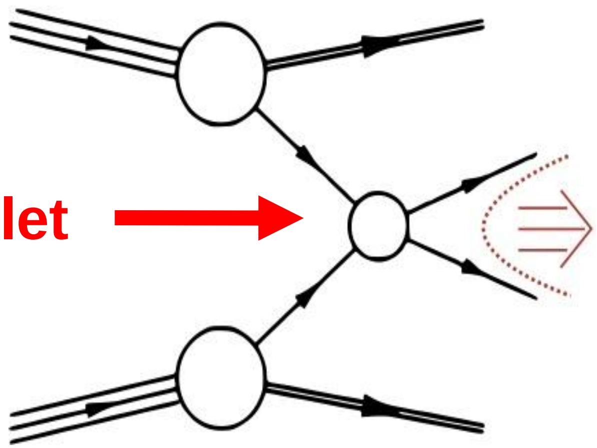
- **Orthogonal channels: combined measurement**
  - **R = 0.90 ± 0.04 (stat+syst), $\sigma_{t\bar{t}}$ = 7.74 $^{+0.67}_{-0.57}$ (stat+syst) pb**
- **Most precise determination of R**
  - **No change if top pair cross section set to be SM value 7.5 $^{+0.6}_{-0.7}$ pb**
  - **R = 0.90 ± 0.04 (2.5 SD with SM value of R ~ 1)**
  - **95% C.L.: 0.82 < R < 0.98, 0.90 < $|V_{tb}|$ < 0.99**
  - **99.7% C.L.: R > 0.77, $|V_{tb}|$ > 0.88**

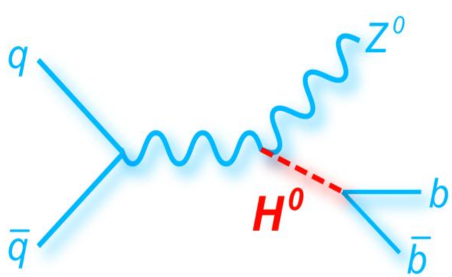
Color Flow

Why color flow?

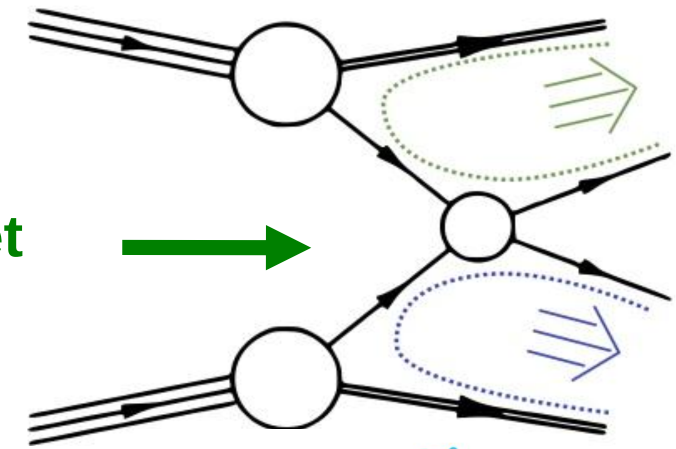
- **Useful tool to separate hadron processes with same final state**
  - **Partons carrying color are "color-connected" to partons with anti-color.**
  - **Hadronization: hadrons form between color-connected partons**

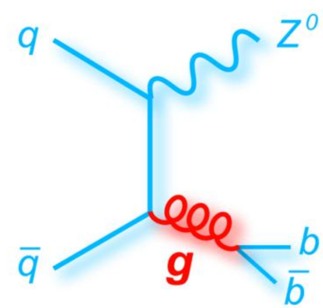
Singlet →





Octet →

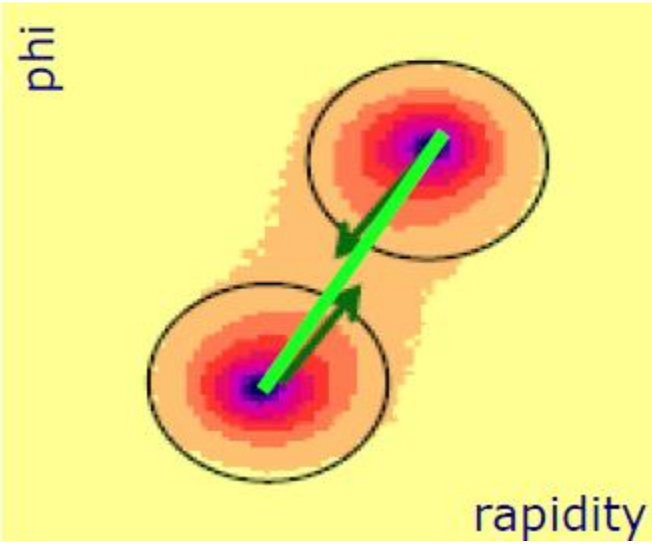




- **h → bb: h is color singlet, b's must be connected to each other**

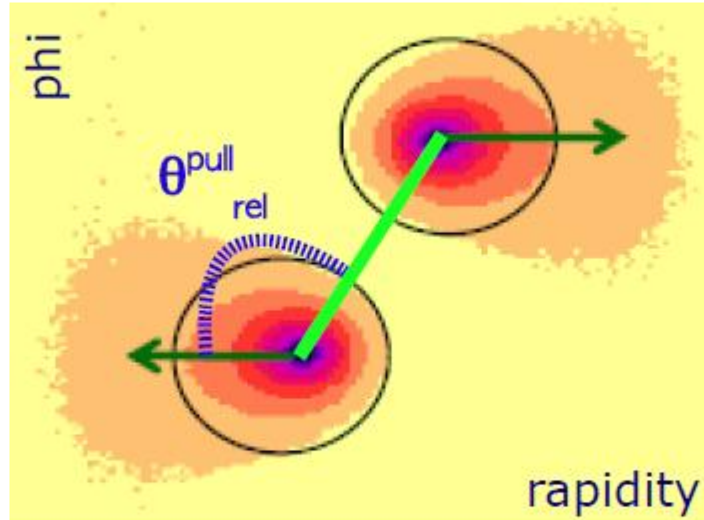
- **qq →Zbb, gg → Zbb: g is color octet, b's are not connected to each other, instead they are more connected to the beam**

Jet Pull

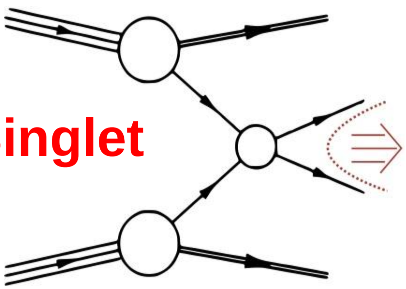


Gallicchio, Schwartz, PRL 105, 022001 (2010)

$$\vec{p} = \sum_i \frac{E_T^i |r_i|}{E_T^{jet}} \vec{r}_i$$



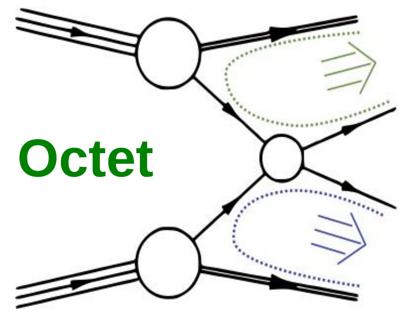
Singlet



Vectorial sum of all cells within a jet

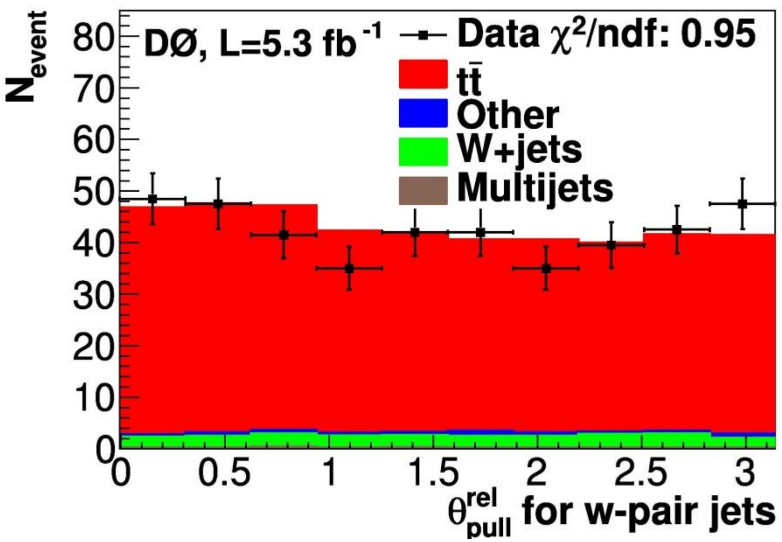
- r_i : point from jet cell *i* to center of jet
- E^i_T: transverse energy of cell *i*
- E^{Jet}_T: transverse energy of jet

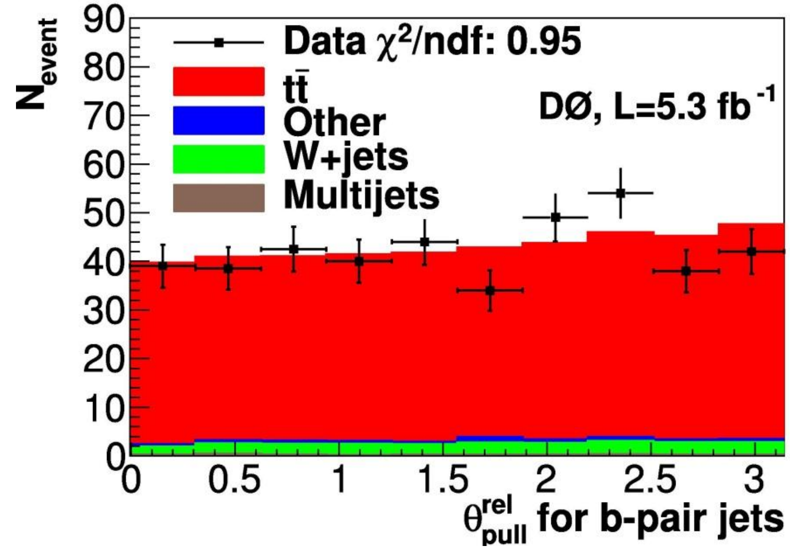
Octet

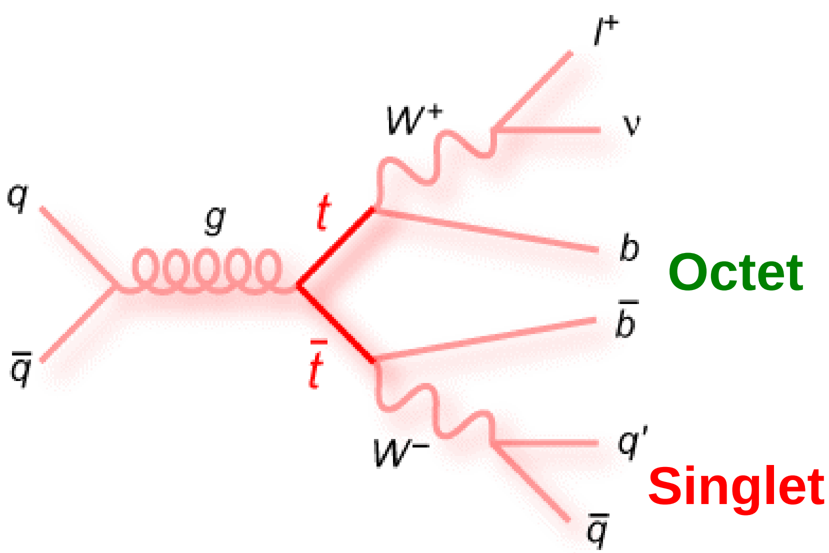


- **"Jet pull" shows the effect of color flow between jets**
- **"Observable θ^{rel}_{pull}": relative angle of the jet pull vector w.r.t. connection line between jet centers; color-connected jets have smaller θ^{rel}_{pull}**

Color Flow Measurement

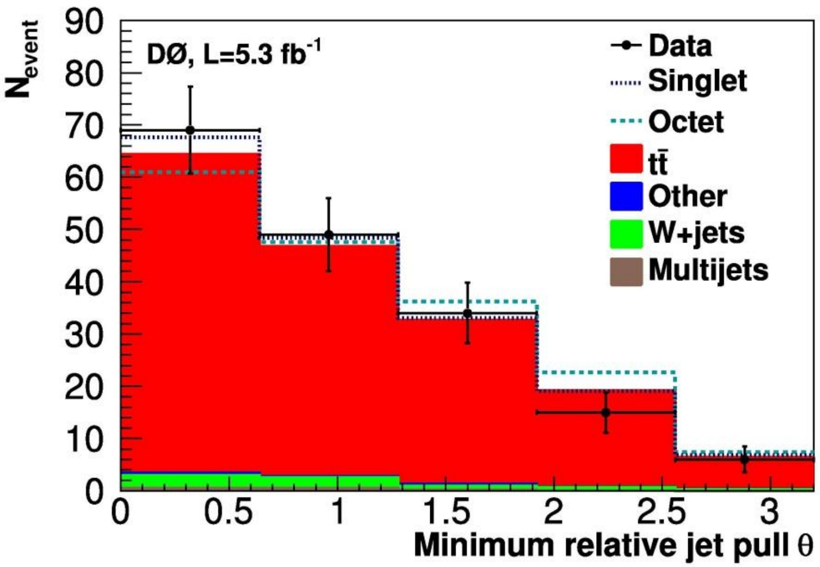


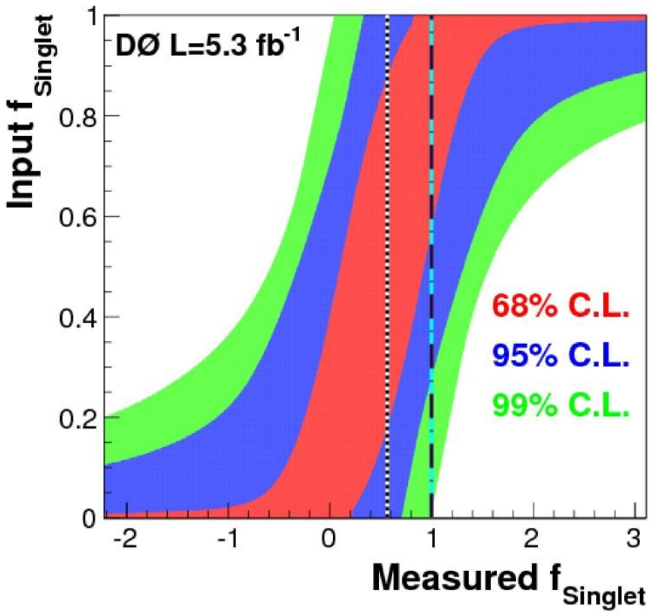




- Tendency of smaller jet pull, θ^{rel}_{pull} seen in *W* pair jets
  - However different kinematics
  - detector and reconstruction effects
- Data well-modeled in each case
  - Verification of color flow simulation and jet pull variable recontruction

Color Flow Measurement





PRD 83, 092002 (2011)

- **Quantify the method's sensitivity to the color-flow structure**
- **Measure fraction of *W* in singlet configuration**
  - $f_{singlet} = N_{singlet} / N_{total}$
  - **Simultaneously fit $\sigma_{t\bar{t}}$ and $f_{singlet}$ to data using discriminant variable θ^{rel}_{pull}**
- $f_{singlet} = 0.56 \pm 0.36$ **(stat)** ± 0.22 **(syst)**
- **Expected: $f_{SM} = 1$, exclude $f_{singlet} = 0$ at 99% C.L. (pseudo-experiments)**

Conclusion

Top Quark cross section being measured at DØ with high precision

- Top pair cross section error ~ 8%
  - Comparable to theoretical uncertainty
  - Important for testing both SM and BSM models
- Top quark branching ratio
- Color flow

Broad top physics programs at DØ

- Top production, top properties and searches
  - http://www-d0.fnal.gov/Run2Physics/top/top_public_web_pages/top_public.html

Backup